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Review on solar air heating system with and without thermal energy storage system

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ABSTRACT

In order to produce process heat for drying of agricultural, textile, marine products, heating of buildings and re-generating dehumidify agent, solar energy is one of the promising heat sources for meeting energy demand without putting adverse impact of environment. Hence it plays a key role for sustainable development. Solar energy is intermittent in nature and time dependent energy source. Owing to this nature, PCMs based thermal energy storage system can achieve the more popularity for solar energy based heating systems. The recent researches focused on the phase change materials (PCMs), as latent heat storage is more efficient than sensible heat storage. In this paper an attempt has been made to present holistic view of available solar air heater for different applications and their performance.

Contents

1. Introduction

The continuous increasing pressure of energy demand, the degradation of environment through greenhouse gas emissions and the rise in fuel prices are the main driving forces behind the efforts for more effectively utilizing various sources of renewable energy. Renewable technologies are considered as clean energy sources and optimal use of these resources minimizes environmental impacts and produces minimum secondary wastes, and such resources are sustainable based on current and future economic and social societal needs. Energy in various forms has been playing an increasingly important role in worldwide economic progress and industrialization. The growth of world population coupled with rising material needs has escalated the rate of energy usage. Rapid increase in energy usage characteristic of the past 50–100 years cannot continue indefinitely as finite energy resources of earth are exhaustible [1]. Therefore, there is a need to explore the renewable energy sources to meet out the energy demand in present context [2]. Solar energy is the one most abundant renewable energy source and emits energy at a rate of 3.8×10^{23} kW, of which, approximately 1.8×10^{14} kW is intercepted by the earth [3]. The primary forms of solar energy are heat and light. Sunlight and heat are transformed and absorbed by the environment in a multitude of ways [4].

One of the most potential applications of solar energy is the supply of hot air for the drying of agricultural, textile, marine products, heating of buildings to maintain a comfortable environment especially in the winter season [5] and re-generating dehumidify

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Nomenclature

A	surface area of absorber plate (m^2)
C_p	specific heat of air (J/kg K)
C_{P_o}	specific heat of air at the outlet (J/kg K)
C_{P_i}	input specific heat of air (J/kg K)
E_c	exergy received by collector (W)
E_f	exergy received by fluid (W)
H_o	output enthalpy (kJ)
H_i	input enthalpy (kJ)
h_0	output specific enthalpy (kJ/kg)
h_i	input specific enthalpy (kJ/kg)
h	heat transfer coefficient (W/m^2 K)
I	intensity of solar radiation (W/m^2)
k	thermal conductivity of air (W/m K)
L	length of test section of duct or long way length of mesh
$\dot{m}$	mass flow rate (kg/s)
Q_u	useful heat gain (W)
Q_c	energy incident on the dryer/evacuated tube (W)
q_u	useful heat flux (W/m^2)
s_i	input entropy (J/kg K)
S_0	output entropy (J/kg K)
T_a	ambient temperature (K)
T_i	inlet temperature (K)
T_0	outlet temperature (K)
T_S	temperature of source (K)
T_{pm}	mean plate temperature (K)
T_{am}	mean air temperature (K)
U_L	overall heat loss coefficient (W/m^2 K)

Greek letters

η_I	first law efficiency of the collector system
η_{II}	second law efficiency of the system
α	absorptance of inner surface of evacuated tube collector
τ	transmittance of the collector tube

agent. Unlike other sources of energy, solar energy can play a significant role for air heating system because the warm air is also the final receiver of energy. This energy possesses a thermal conversion mode which necessitates a simple technology which is adapted to the site and to the particular region for many applications. All these systems are based on the solar air collectors. Solar energy collectors are employed to gain useful heat energy from incident solar radiation. They can be concentrating or flat plate type [6]. Solar air heater can be used in a wide variety of applications, but it is a limited resource.

Solar energy is intermittent in nature and time dependent energy source. Conversion of solar energy into thermal energy is the easiest and the most widely accepted method. Due to this nature, thermal energy storage system can play an important role in popularization of the solar energy based systems. Thermal energy can be stored as sensible heat, latent heat or chemical energy. Latent heat storage systems using phase change material (PCM) is a particularly attractive technique, since it provides a high energy storage density and has the capacity to store heat as latent heat of fusion at a constant temperature. Thermo-physical properties of the storage material (PCMs) at this temperature are important in determining the *suitability* of the material [7]. The recent researches focused on the phase change materials based air heating systems, because it has high energy storage density compared to sensible heat storage and suitability for optimum thermal performance of solar air heater. In this present communication, a generous holistic view on different air heating system with and without storage systems and its potential applications are presented.

2. Classification of air heaters

Solar air heater is a device in which energy transfer is from a distant source of radiant energy to air. Solar air heaters can be used for many purposes, including crop drying, space heating, and for re-generating dehumidifying agents [8–10]. It is a difficult task to classify solar air heaters in proper manner. There are numbers of configurations and many of which are empirical constructions. They can be classified on the basis of mode such as active, hybrid and passive. A comprehensive review on various designs, construction and operation principles of a wide variety of solar air heater for drying is given by Ekechukwu and Norton [11]. Here we are trying to classify the solar heater on the basis of energy storage, numbers of covers, extended surface and their tracking axis and it is presented in Fig. 1. Hot air is generated at different places and direct it to end use in the active solar air heating systems but it can be more expensive to construct in comparison of passive systems. Simultaneously, active solar air heating systems are easier to design because of their forced air operation. Energy storage materials are widely used in active type solar air heater to supply hot air during off sunshine hours. Passive air heaters are generally regarded and used as daytime heaters.

3. Thermal performance of solar air heater

3.1. Energy analysis

Heat and energy transfer phenomenon with in air heater is illustrated in Fig. 2. The brief analysis of thermal performance of such system is described by Grag and Prakash [12].

Thermal performance of solar air heater can be computed with the help of Hottel–Whillier–Bliss equation reported by Duffie and Beckman [13].

$$Q_u = A_C F_R[I(\tau\alpha)_e - U_L(T_i - T_a)]$$

or

$$q_u = \frac{Q_u}{A_C} = F_R[I(\tau\alpha)_e - U_L(T_i - T_a)]$$

The rate of valuable energy gain by flowing air in the course of duct of a solar air heater can be intended as follows:

$$Q_u = \dot{m}C_p(T_o - T_i) = hA_C(T_{pm} - T_{am})$$

The value of heat transfer coefficient (h) can be increased by applying artificial roughness on the on the surface of absorber plate. Basically it represent in nondimensional form of Nusselt number (Nu) reported by Duffie and Beckman [13].

$$Nu = \frac{hL}{k}$$

Thermal efficiency of solar air heater can be expressed by the following equation:

$$\eta_{th} = \frac{q_u}{I} = F_R\left[(\tau\alpha)_e - U_L\left(\frac{T_i - T_a}{I}\right)\right]$$

4. Exergy analysis

The rate at which exergy is collected by the solar collector can be increased by increasing the mass flow rate of the working fluid. Since, the collector is the most expensive component of solar air heating system. Here we are considering in the case of evacuated tube collector for air heating. In order to reduce the capital cost, we

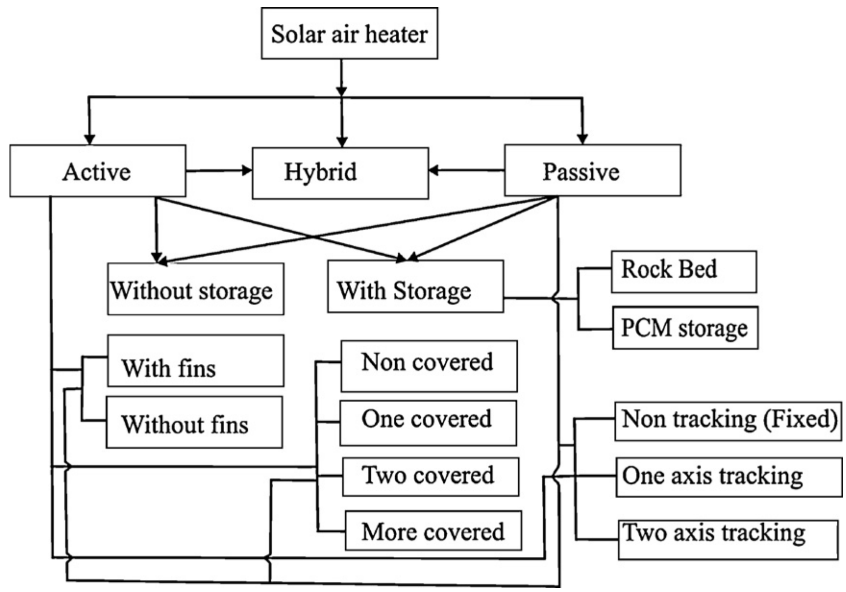


Fig. 1. Classification of solar air heaters.

need to optimize the dryer area, as the fuel (sunlight) is free. Again, for large mass flow rates, the fluid outlet temperature is very low and requires more power to pump/blow air/fluid through it. On the other hand, low flow rate results in high outlet temperature of the working fluid with high specific work potential. But due to the nature of entropy generation, exergy losses increase due to the temperature differences and hence, the optimum mass flow rate is required. The exergy received by collector is given by [14–20]:

$$E_c = Q_C\left(1-\left(\frac{T_a}{T_S}\right)\right) \tag{5}$$

The exergy received by fluid is written as [8–11,23–25]:

$$E_f = \dot{m}(E_O - E_i) = \dot{m}[(h_O - h_i) - T_a(s_O - s_i)] \tag{6}$$

The output specific enthalpy of the fluid is given by [18–20]:

$$h_o = C_{P_o}T_O \tag{7}$$

The specific enthalpy of inlet air is given by [18–20]:

$$h_i = C_{P_i}T_i \tag{8}$$

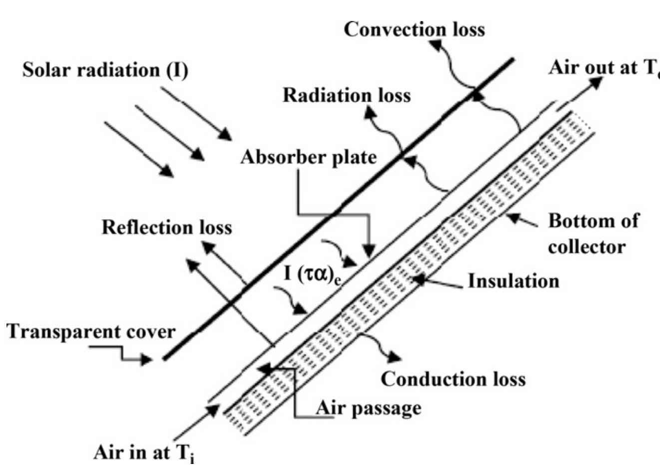


Fig. 2. Conventional solar air heater.

While the entropy difference has been calculated using the following set of equations [18–20]:

$$C_{P_i} = a + k \times T_i \tag{9}$$

$$C_{P_O} = a + k \times T_O \tag{10}$$

$$ds = \frac{dq}{T} = \frac{C_p dT}{T} = (a + bT)\left(\frac{dT}{T}\right) = \frac{adT}{T} + kdT \tag{11}$$

Using Eqs. (9) and (10), the values of constants a and k can be calculated and hence, the entropy difference thereafter using Eq. (11). The second law efficiency of the system can be written as [8–11,23–25]:

$$\eta_{II} = \frac{E_f}{E_C} = \frac{\dot{m}[(h_O - h_i) - T_O(s_O - s_i)]}{Q_C(1 - T_O/T_S)} \tag{12}$$

and first law efficiency can be written as [19]:

$$\eta_I = \frac{\dot{m}(h_O - h_i)}{Q_C} \tag{13}$$

$$H_O\left(\frac{KJ}{\text{sec}}\right) = \dot{m} \times h_o \tag{14}$$

$$H_i\left(\frac{KJ}{\text{sec}}\right) = \dot{m} \times h_i \tag{15}$$

$$Q_C = 4AI_s \cos 45 \times \tau \times \alpha \tag{16}$$

where a and k are constants, η_I is the first law efficiency and η_{II} is the second law efficiency of the solar collector–dryer system.

4.1. Solar air heaters without thermal energy storage

Various types of solar air-heaters are being used for different applications; among them flat-plate collectors are extensively used in low-temperature solar energy, because they are relatively simple, easy to operate and have low capital costs [21]. Solar air heaters have many attractive advantages over liquid heaters regarding the problems of corrosion, boiling, freezing and leaks [22]. Solar air heater without thermal storage is extensively used for drying agriculture products. Basically most of the agriculture products are getting dried at low temperature (50–60 °C) and this can be easily achieved in flat plate type solar air heater. Further hot air generated by air heater can be delivered by natural convection by force convection. Solar air heater with natural convection mode is found

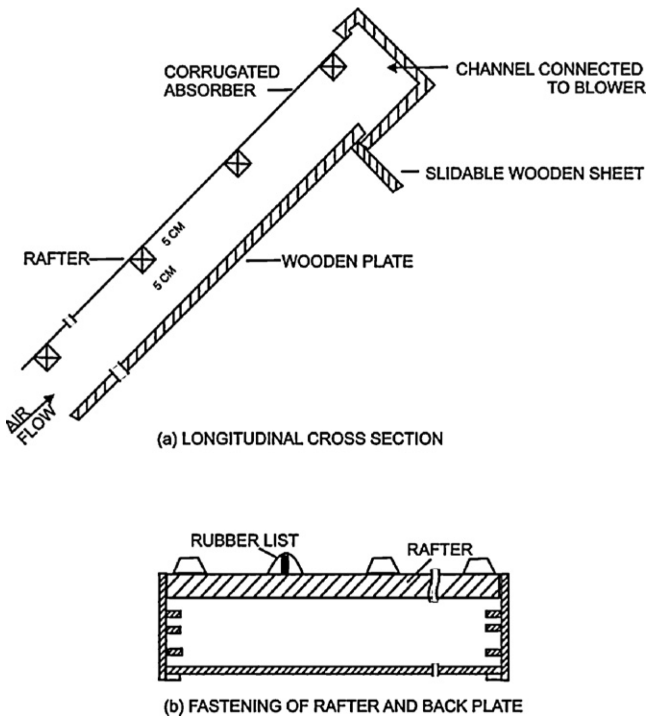


Fig. 3. Construction details of the test air heaters.

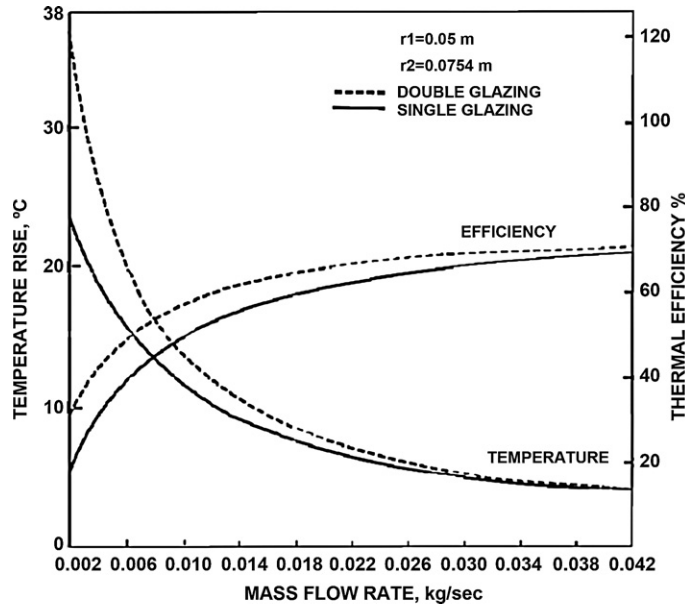


Fig. 4. Variations of temperature rise and efficiency of the collector with mass flow rate for single and double glazings.

most suitable in rural area of developing and under developing nations where electricity is either not available or available for short duration of time [23]. A widespread literature reviewed various types of solar air heater without thermal storage and presented in this section.

A bare plate roof air heater was fabricated from corrugated aluminum sheet roof in farm shed to provide hot air for agricultural use by Choudhury et al. [24] as shown in Fig. 3. The performance efficiency of such a roof air heater is observed to be strongly influenced by the design parameters of the system. It was reported that higher air temperature, lower air mass flow rate through air heater and longer air channel is desirable. The performance of the cylindrical matrix type solar air heater with the effect of single and double glazing was evaluated by Bansal and Singh [25]. It was noted that for high flow rates of the air, the efficiency reaches a high value up to 70% as shown in Fig. 4. It was also reported that, radial size of the cylindrical matrix naturally alters the performance of the system. The relevance of porous material in the erection of the solar energy collectors is well known. The heat transfer in a porous plate, subjected to solar radiation, is highly effective in both heating the working fluid and improving the absorption characteristics of the plate [26,27]. The experimental studies on two non-porous solar absorber solar air heaters with and without fins have been reported by Indrajit et al. [28]. During experiments it was found that air heaters with fins are seen more efficient in comparison to the air heater without fins for air flow rates $\leq$0.0388 kg/s/m^2.

Singh and Bansal [29] fabricated solar air heater from broken glass pieces and evaluated with four typical cases (i) top surface blackened, (ii) all glass pieces blackened and (iii) bottom surface blackened. The general conclusions drawn from the results are (1) The efficiency of all three systems goes on increasing with increasing mass flow rate. (2) Porous types of air heaters always give better performance over the nonporous types, since the bottom absorbing type of air heater is better than the top absorbing type of air heater. (3) For the case of non-porous types of air heating collectors, the thin and thick absorbing plates are better for absorption at the top and bottom, respectively, while a porous type air heater has an optimum plate thickness (i.e. 0.05 m). (4) The glazing on the top and insulation at the bottom has equal importance in porous types of air heaters. Analytical and experimental studies have been carried out on the thermal performance of cross-corrugated solar air-heaters for several configurations and operating conditions by Gao et al. [30]. Air heater used for this study consisted of a wave-like absorbing-plate and a wave-like bottom-plate, which are cross-wise positioned to form the air flow channel. Two types of heaters were considered. The type 1 heater has a wave-like shape of the absorbing plate, which is along the flow direction and that of the bottom plate is perpendicular to the flow direction as shown in Fig. 5, while in the type 2 heater, it is the wave-like shape of the bottom plate as well as along the flow direction, and that of the absorbing plate is perpendicular to the flow direction. The following conclusions were made: (1) The thermal performance of the type 2 heater is just slightly superior to that of the type 1 heater; both these cross-corrugated solar air heaters have a significantly superior thermal performance to that of the flat-plate one, with the achievable efficiencies of 58.9%, 60.3% and 48.6% for the type 1, type 2 and flat-plate solar air-heaters, respectively, under the typical configurations and operating conditions. (2) The use of selected coatings on the absorbing plates of all the heaters considered can substantially enhance the thermal performances of the heaters and therefore its use is strongly recommended in practical applications, whereas such a selected coating is not recommended for the bottom plates and the glass covers. (3) The experimental results also support the conclusion that the use of the cross-corrugated wave-like absorbing-plate and bottom-plate does significantly improve the thermal performance of a solar air heater.

Bhargava and Rizzi [31] designed cost-effective solar air heaters, where a partial flow channel between two glazings increases the efficiency of the system. Proposed design helps to eliminate the need for insulation material, at least on the two sides of the space between two glazings. It was concluded that the upper glazing should be as transparent as possible while the lower glazing should have higher absorptance. A solar air heater was designed, fabricated with locally available low-cost materials and its performance was assessed in the perspective of an emerging/developing country with a huge energy demand like Bangladesh by Wazed et al. [32]. The air temperature obtained in the test room was noteworthy. In

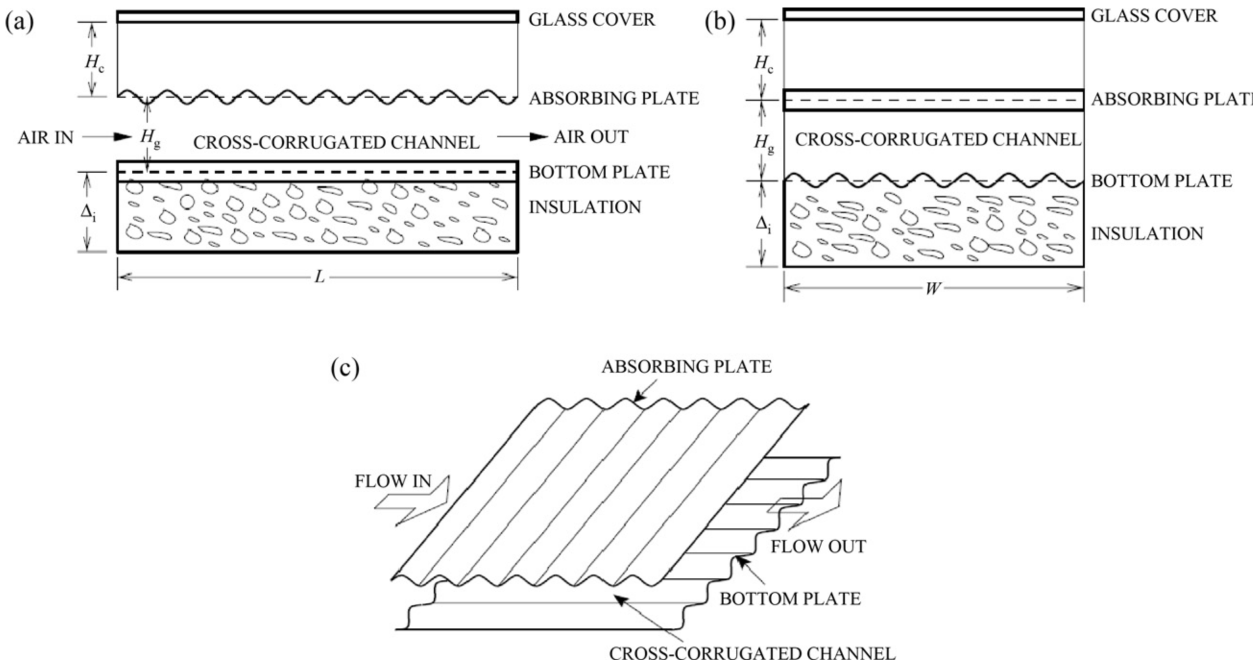


Fig. 5. Schematic description of the type 1 solar air heater (a) cross-section view perpendicular to the flow direction; (b) cross-section view along the flow direction; and (c) schematic description of the cross-corrugated absorbing plate and bottom plate.

forced circulation, the maximum room temperature obtained was 45.5 °C and the maximum difference from ambient was 12.25 °C. In case of natural circulation, the maximum room temperature obtained was 41.75 °C and the maximum difference from ambient was 8.5 °C. The room temperature is higher in forced circulation, because the total volume of air circulates for more times in this case. The difference between ambient and room temperatures was also higher. The efficiency was also higher in case of forced circulation than that of natural.

A unique jet impingement concept to achieve higher heat transfer from the absorber plate to the flowing air stream with an intention to increase the amount of the collected energy, and hence, to improve the efficiency of an air-based solar collector was introduce by Choudhury and Garg [33]. The gain in air temperature increment and performance efficiency of the jet concept air heater (without cross flow) over that of a conventional parallel plate air heater with channel length 2 m and depth 10 cm was 15.5–2.5 °C and 26.5–19%, respectively, for air flow rates in the range 50–250 kg/hm^2. The efficiency of the jet plate air heater without cross flow remains insensitive to the change in duct length, whereas with cross flow, an increase in length results in a decrease in the system efficiency. The pumping pressure in a solar air heating system has significant influence on efficiency through the heat transfer coefficient.

On-farm crop drying is frequently essential to prevent mold growth and spoilage of mechanically harvested crops. Keeping this in view suspended-plate solar air heaters were installed on farms in Tennessee by Womac et al. [34] to supply heat for grain and crop drying. Designs included a wrap-around heater, a portable heater and a multipurpose barn. The heaters were telemetrically monitored to determine thermal performance and to allow subsequent analyses of economic feasibility. Thermal analysis of system revealed that solar air heaters provide a suitable air temperature rise during most crop drying conditions. The heaters operated with average thermal efficiencies in the range of 50–70%. Economic analyses indicated that solar air heaters are economically feasible if they are used at least 2 months per year assuming not more than 14% annual interest and at least 4% annual fuel inflation. Similar type of suspended plate solar air heater was studied by Pawar et al. [35] as shown in Fig. 6. It was concluded that the shorter length of the channel of the order of 1.5–2.5 m is desirable to get higher efficiency. The depth of the channel in such an air heater should be as narrow as possible. A little advantage in heat gain was obtained when the depth of the upper and lower channels were equal. Thus, the absorber plate should be located at the center in the collector. Energy and exergy analysis of three different types of designed flat-plate solar air heaters as shown in Fig. 7, two having fins (type II and type III) and the other without fins (type I), one of the heater with a fin had single glass cover (type III) and the others had double glass covers (type I and type II) was carried out by Alta et al. [36]. The energy and exergy output rates of the solar air heaters were evaluated for various air flow rates (25, 50 and 100 m^3/m^2 h), tilt angle (0°, 15° and 30°) and temperature conditions versus time. Based on the energy and exergy output rates, heater with double glass covers and fins (type II) is more effective and the difference between the input and output air temperature is higher than of the others. Besides, it was found that the circulation time of air inside the heater played a role more important than of the number of transparent sheet. Lower air flow rates should be preferred in the applications, in which temperature differences are more important.

Yeh and Ho [37] investigate theoretical efficiency of solar air heaters with external recycle as shown in Fig. 8. They found that there are two major problems associated with the use of external-recycle in solar air heaters. One is the desirable effect of increasing fluid velocity to decrease the heat transfer resistance. The other is the undesirable effect of decreasing the driving force (temperature difference) of heat transfer, due to the remixing at the inlet. They

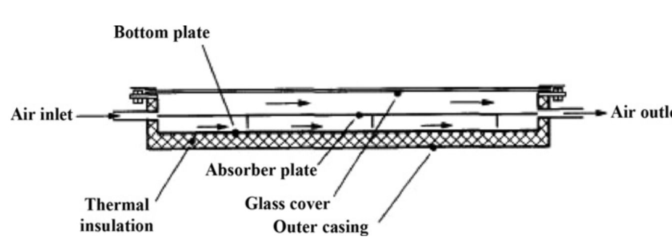


Fig. 6. A cross sectional view of developed air heater.

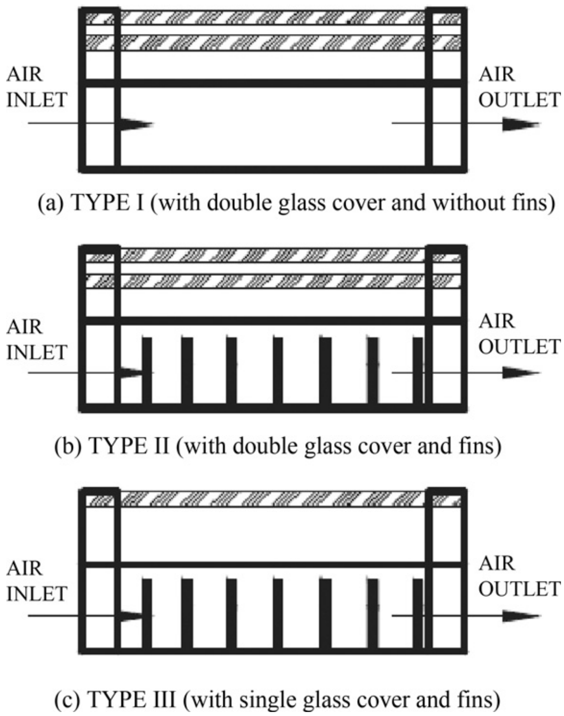


Fig. 7. Construction details of type I, type II and type III.



Fig. 9. Photograph of the solar air heater.

reported that considerable improvement in collector efficiency is obtainable if the operation is carried out with an external recycle, where the desirable effect overcomes the undesirable effect. The enhancement increases with increasing reflux ratio, especially for operating at lower air flow rate with higher inlet air temperature.

An economic analysis of a roof-integrated solar air heating system as shown in Fig. 9, for drying fruit and vegetables was carried out by Sreekumar [38]. The system was found efficient and economically viable and it was experimentally proved for drying pineapple. Economic analysis showed that the cumulative present worth of annual savings for drying bitter gourd over the life of the solar dryer turned out to be approximately 17 million rupees. The capital investment of the dryer was Rs. 550,000 and the payback period of the dryer was found to be 0.54 year, which is very short considering the life of the system. The cost of drying pineapple in the solar dryer was only about 20% of drying it in electric dryer. The life of the system was expected to be 20 years, because the material used in the construction is corrosion proof. The thermal performance of a double flow solar air heater (SHA) as illustrated in Fig. 10, was experimentally evaluated by Ozgen et al. [39]. The absorbing plate of SHA was made of aluminum cans into the double-pass channel. It substantially improves the collector efficiency by increasing the fluid velocity and enhancing the heat-transfer coefficient between the absorber plate and air. These types of collectors had been designed as a proposal to use aluminum materials to build absorber plates of SAHs at a suitable cost. During the study the collector was covered with a 4-mm single glass plate, in order to reduce convective loses to the atmosphere. Three different absorber plates were designed and tested for experimental study. In the first type (type I), cans had been staggered as zigzag on absorber plate, while in type II they were arranged in order. Type III is a flat plate (without cans). Experiments were performed for air mass flow rates of 0.03 kg/s and 0.05 kg/s. The highest efficiency was obtained for type I at 0.05 kg/s. In similar manner other experiments on single and double pass solar air heater with fins attached and using a steel wire mesh as absorber plate were investigated by Omojaro and Aldabbagh [40]. Schematic of single and double pass solar air heater is presented in Fig. 11. During the experiments it was found that, the efficiency increases with increasing air mass flow rate. For the same flow rate, the efficiency of the double pass is found to be higher than the single pass by 7–19.4%. Maximum efficiency obtained for the single and double pass air heater was 59.62% and 63.74%, respectively for air mass flow rate of 0.038 kg/s. The temperature difference between the outlet flow and the ambient, temperature difference, reduces as the air mass flow rate increases. The result of a single or double solar air heater using steel wire mesh arrange in layers as an absorber plate and packing material when compared with a conventional solar air heater shows a much more substantial enhancement in the thermal efficiency.

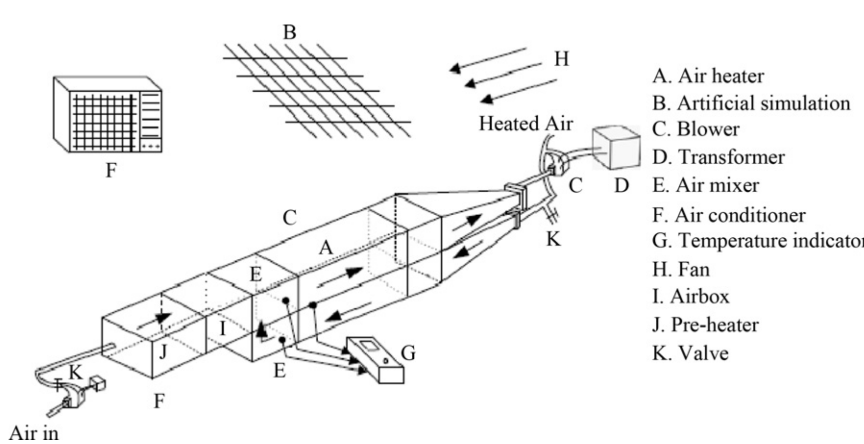


Fig. 8. An actual panel of solar air heater.

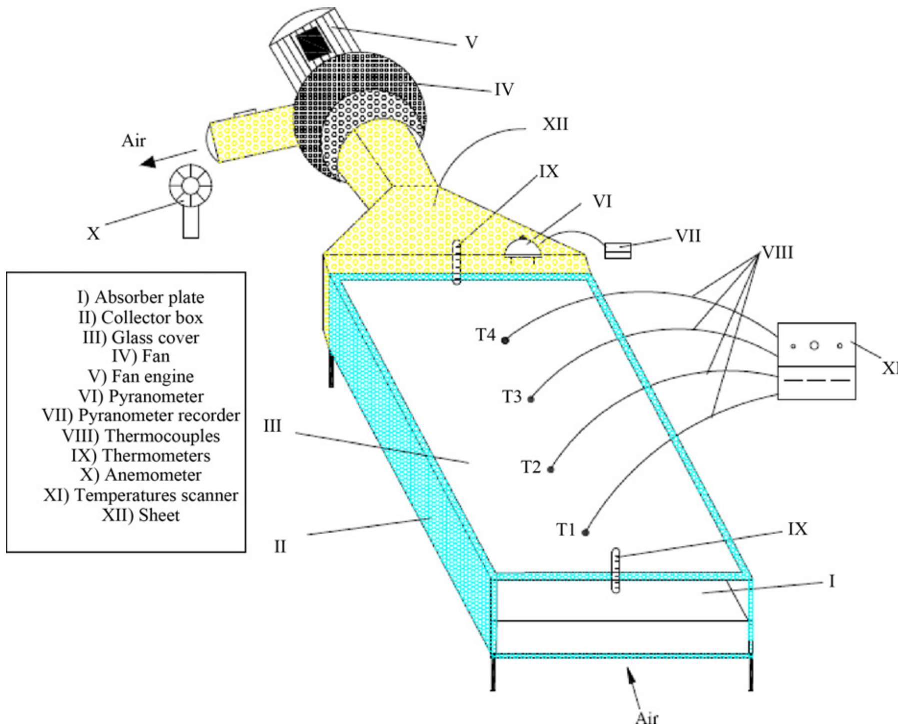


Fig. 10. Schematic assembly of the SAH system.

Mohamad [41] presented a novel type of solar air heater with an idea to minimize heat losses from the front cover of the collector and to maximize heat extraction from the absorber. This can be done by forcing air to flow over the front glass cover (preheat the air) before passing through the absorber. Hence, this design needs an extra cover to form a counter-flow heat exchanger. Porous media forms an extensive area for heat transfer, where the volumetric heat transfer coefficient is very high. The thermal efficiency of this type of collector is significantly higher than the thermal efficiency of conventional air heaters and it exceeds 75% under normal operating conditions. An analytical model for double pass flat and v-corrugated plate solar air heaters for Tanta (latitude, 30°47′N) weather conditions was presented by El-Sebaii et al. [42]. The results showed that the double pass v-corrugated plate solar air heater is 11–14% more efficient compared to the double pass flat plate solar air heater. It was also reported that the peak values of the thermo hydraulic efficiencies of the flat and v-corrugated plate solar air heaters are obtained when the mass flow rate of the flowing air is 0.02 kg/s. Naphon [43] developed a mathematical model to evaluate thermal performance and entropy generation of the double-pass flat plate solar air heater with longitudinal fins as shown in Fig. 12. This model was based on study conducted by Naphon and Kongtragool [44] with the assumption that (a) flow of air is steady, (b) air-side convective heat transfer coefficient is constant along the length of solar air heater, (c) tube-side convective heat transfer coefficient is constant along the length of solar air heater and (d) thermal conductivity of fin is constant along the length of solar air heater. The predictions were done at air mass flow rate ranging between 0.02 and 0.1 kg/s. It was found that the thermal efficiency increases with increasing the height and number of fins. The entropy generation is inversely proportional to the height and number of fins.

4.2. Solar air heater with thermal energy storage

Solar air heater with PCM based thermal storage system is the solar energy collection for it's off sunshine hours use. A phase change material is a solid and melted which stores energy. The melting temperature may be fixed or may vary over a small range. The stored energy is recovered upon solidification of the liquid. In this system, solar energy stored in thermal energy storage system (TESS), during sunny days and recovered later at night or during cloudy days. Different phase change materials (PCMs) are available for this temperature range, usually hydrated salts (such as calcium chloride hexahydrate, Glauber's salt), paraffins, non-paraffins and fatty acids [45–48] are very popular materials. Potential phase change materials for air heating system are given in Table 1. A comprehensive review has been made in this regard and presented in this section.

Jurinak and Abdel-Khalik [49] have presented a parametric study to determine the optimum physical properties of phase-change energy storage materials for solar air-heating systems. They used simulation techniques to determine the system performance over the entire heating season for different space heating load. They [50] also described the transient behavior of phase-change energy storage (PCES) units and presented simulation techniques to use in conjunction with these models to determine the performance of solar heating systems utilizing PCES. They used sodium sulfate decabydrate and paraffin wax as a storage media for air heating system and calculated optimum ranges of storage sizes, the variation of the solar supplied fraction of load with storage size and collector area for systems.

Hammou and Lacroix [51] proposed a hybrid thermal energy storage system (HTESS), using phase change materials for managing simultaneously the storage of heat from solar and electric energy as shown in Fig. 13. A schematic diagram of the HTESS is given in figure. They stored solar heat during sunny days and released later at night or during cloudy days and, to smooth power demands, electric energy is stored during off-peak periods and later used during peak periods. The results of this study indicate that, by using a HTESS, the electricity consumption for space heating is reduced by 32%. Also, more than 90% of the electricity is consumed during off-peak hours. For electricity markets where time-of-use rate schemes are in effect, the return on the investment in such a

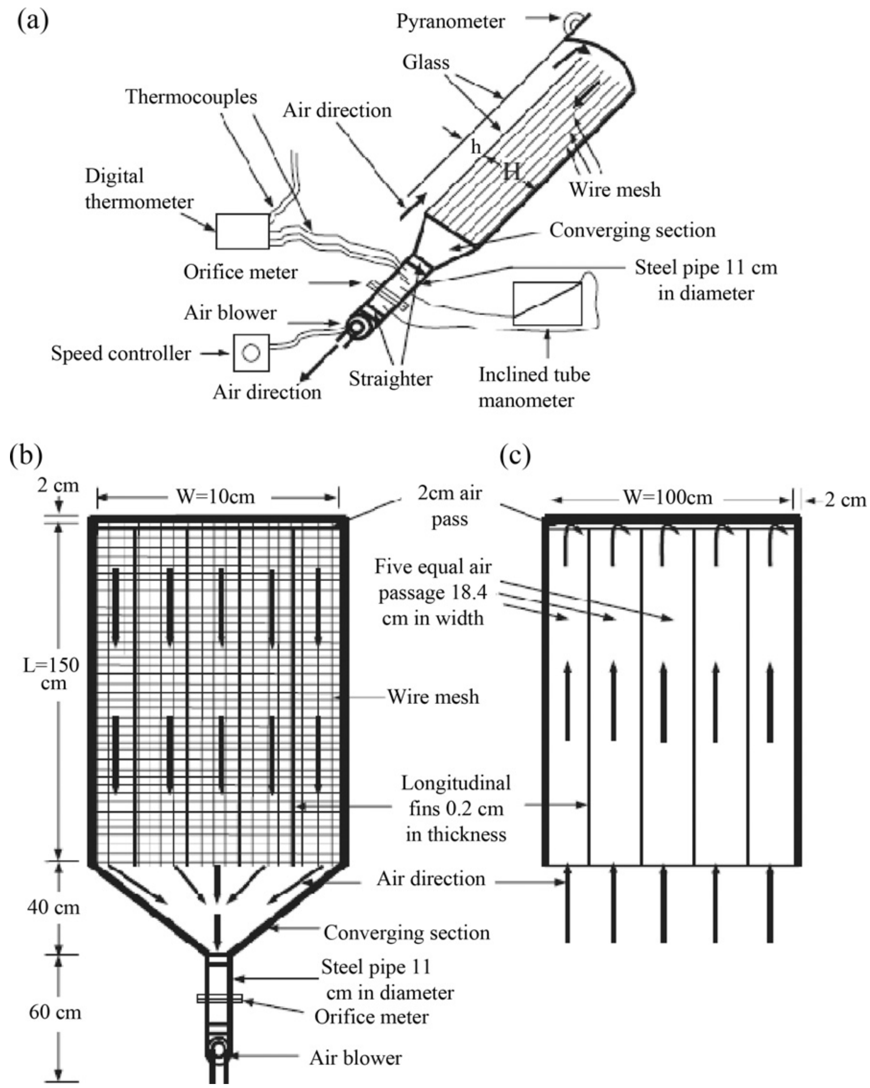


Fig. 11. Single and double pass solar air heater showing: (a) schematic diagram of the experimental setup, (b) lower pass channel, and (c) upper pass channel.

storage system is very attractive. Qi et al. [52] studied on solar heat pump heating system with seasonal latent heat thermal storage (SHPH–SLHTS). They develop a mathematical model for the system and the simulated operating performances of the system. The simulation results suggested that the temperature of the PCM in a storage tank was much lower than that of water in a central solar heating system with hot-water heat storage, and could be maintained at around the melting point of the PCM. The losses of the system from the storage tank to ambient are reduced in SHPH–SLHTS system and the storage volume of a SHPH–SLHTS system is smaller comparatively with central solar heating system with seasonal storage system.

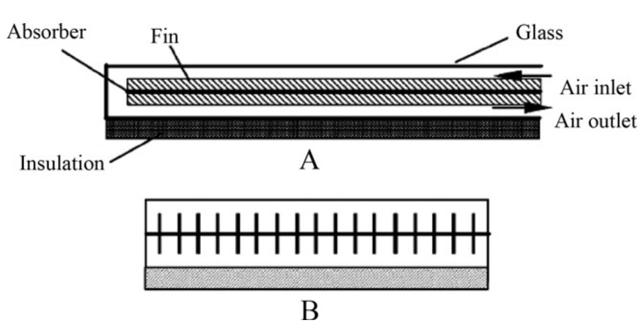


Fig. 12. Schematic diagram of the solar air heater.

Kaygusuz [53] investigated experimentally and theoretically the performance studies of a solar heating system with a heat pump. Experimental studies show that the parallel heat pump system saved more energy than the series heat pump system, because it uses both air and solar as a heat source for the evaporator while the series system uses only solar energy stored in the storage tank. In this experimental study, they used $CaCl_2{\cdot}6H_2O$ as a PCM and concluded that it is technically preferable as a storage material in this region. The experimental results of this study indicate that high collector efficiencies ranging from 62 to 70% can be realized with 30 m^2 flat-plate water cooled collectors over the heating period for the solar assisted series heat pump with energy storage as illustrated in Fig. 14, while the collector efficiency of the parallel heat pump system ranged from 54 to 60%. However, energy storage efficiencies were less than the collector efficiencies. The average net storage efficiency is 63% for both systems. The average seasonal heating performance values are 4.0 and 3.0 for series and parallel heat pump systems, respectively. In this study, a thermodynamic model has been developed for a solar assisted series heat pump system with latent heat energy storage. The system parameters were determined from experimental data. It was found that the model agreed well with the experimental results. Nallusamy et al. [54]

Table 1
Potential phase change materials for air heating system.

Materials	Melting point (°C)	Latent heat (kJ/kg)
Organic materials		
Capric acid	36	152
Eladic acid	47	218
Lauric acid	49	178
Pentadecanoic acid	52.5	178
Tristearin	56	191
Myristic acid	58	199
Palmatic acid	55	163
Stearic acid	69.4	199
Acetamide	81	241
Inorganic materials		
$Zn(NO_3)_2{\cdot}6H_2O$	36.1	134
$FeCl_3{\cdot}6H_2O$	37.0	223
$Mn(NO_3)_2{\cdot}4H_2O$	37.1	115
$Na_2HPO_4{\cdot}12H_2O$	40.0	279
$CoSO_4{\cdot}7H_2O$	40.7	170
$KF{\cdot}2H_2O$	42	162
$MgI_2{\cdot}8H_2O$	42	133
$CaI_2{\cdot}6H_2O$	42	162
$K_2HPO_4{\cdot}7H_2O$	45.0	145
$Zn(NO_3)_2{\cdot}4H_2O$	45	110
$Mg(NO_3){\cdot}4H_2O$	47.0	142
$Ca(NO_3){\cdot}4H_2O$	47.0	153
$Fe(NO_3)_3{\cdot}9H_2O$	47	155
$Na_2SiO_3{\cdot}4H_2O$	48	168
$K_2HPO_4{\cdot}3H_2O$	48	99
$Na_2S_2O_3{\cdot}5H_2O$	48.5	210
$MgSO_4{\cdot}7H_2O$	48.5	202
$Ca(NO_3)_2{\cdot}3H_2O$	51	104
$Zn(NO_3)_2{\cdot}2H_2O$	55	68
$FeCl_3{\cdot}2H_2O$	56	90
$Ni(NO_3)_2{\cdot}6H_2O$	57.0	169
$MnCl_2{\cdot}4H_2O$	58.0	151
$MgCl_2{\cdot}4H_2O$	58.0	178
$CH_3COONa{\cdot}3H_2O$	58.0	265
$Fe(NO_3)_2{\cdot}6H_2O$	60.5	126
$NaAl(SO_4)_2{\cdot}10H_2O$	61.0	181
$NaOH{\cdot}H_2O$	64.3	273
$Na_3PO_4{\cdot}12H_2O$	65.0	190
$LiCH_3COO{\cdot}2H_2O$	70	150
$Al(NO_3)_2{\cdot}9H_2O$	72	155
$Ba(OH)_2{\cdot}8H_2O$	78	265

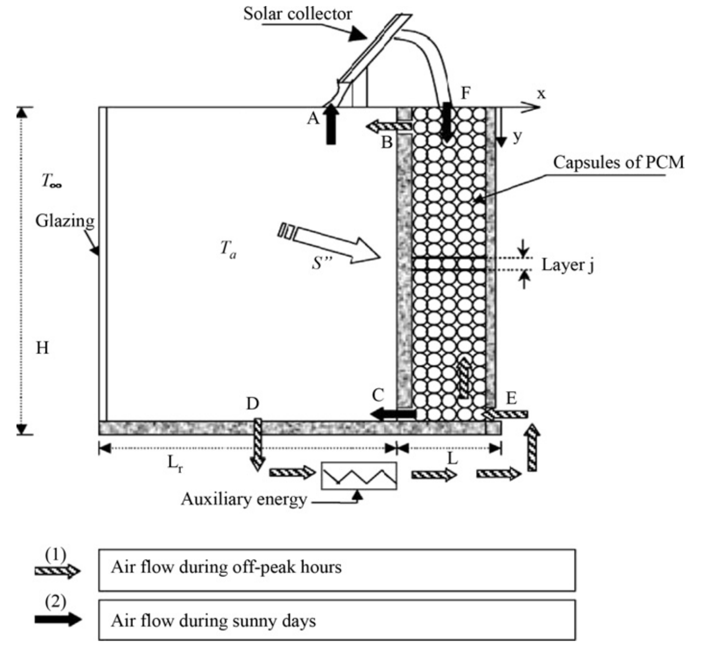


Fig. 13. Schematic of the hybrid thermal energy storage system.

experimentally investigate the thermal behavior of a packed bed of combined sensible and latent heat thermal energy storage (TES) unit. A TES unit is designed, constructed and integrated with constant temperature bath/solar collector to study the performance of the storage unit. The TES unit contains paraffin as phase change material (PCM) filled in spherical capsules, which are packed in an insulated cylindrical storage tank. Charging experiments are carried out at constant and varying (solar energy) inlet fluid temperatures to examine the effects of inlet fluid temperature and flow rate of HTF on the performance of the storage unit. They concluded that in the case of constant inlet HTF temperature, the mass flow rate has only a small effect on the rate of charging, as the surface resistance is not significant compared to the varying resistance offered inside

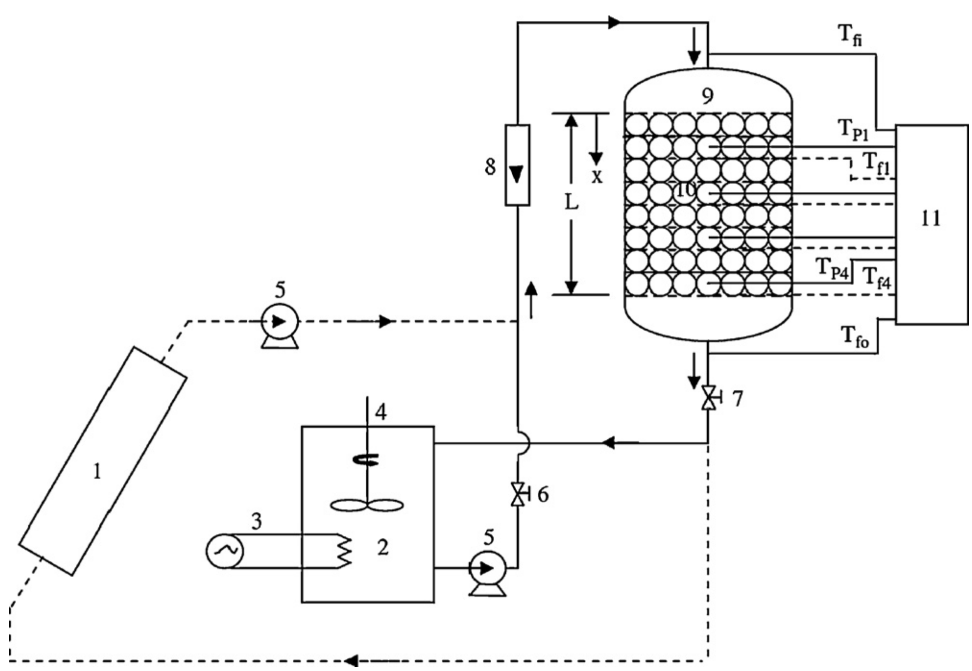


Fig. 14. Schematic of experimental setup solar flat plate collector with PCM capsules based heating system.

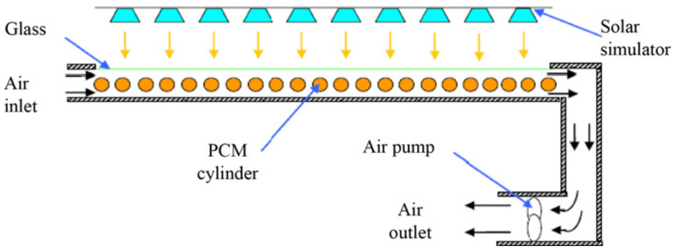


Fig. 15. Cross section of the solar air collector with PCM cylinders.

the PCM capsules and the rate of heat transfer increases in direct proportion with the increase in inlet temperature of the HTF. In the case of the storage unit integrated with solar flat plate collector, the mass flow rate has significant effect on the heat extraction rate from the collector, which in turn affects the rate of charging of the TES tank. Experiments are conducted for continuous discharging and batch wise discharging for both SHS system and combined storage system. It is concluded that the combined storage system gives better performance than the conventional SHS system where there is a direct mixing of the HTF with the hot water in the storage tank.

Mettawee and Assassa [55] designed and studied of a compact phase change material (PCM) solar collector based on latent heat storage material. In this collector, the absorber plate-container unit performs the function of both absorbing the solar energy and storing this heat into the PCM. The paraffin wax was used as a PCM for solar heat and was discharged to cold water flowing in pipes located inside the wax. The experimental apparatus was designed to simulate one of the collector's sectors, with an apparatus-absorber effective area of 0.2 m^2. The time-wise temperatures of the PCM were recorded during the processes of charging and discharging. The experimental results showed that in the charging process, the average heat transfer coefficient increases sharply with increasing the molten layer thickness, as the natural convection grows strong. Zhao et al. [56] studied on a solar air heating system for building heating season (from November to March) and hot water supply all year around in North China. Total five different working modes were designed based on different working conditions: (1) heat storage mode, (2) heating by solar collector, (3) heating by storage bed, (4) heating at night and (5) heating by an auxiliary source. These modes can be operated through the on/off control of fan and auxiliary heater and through the operation of air dampers manually. They used solar fraction of the system as the optimization parameter. They used TRNSYS program to analyze the solar collector area, installation angle of solar collector, mass flow rate through the system, volume of pebble bed, heat transfer coefficient of the insulation layer of the pebble bed and water storage tank, height and volume of the water storage tank. The results of system showed that the designed solar system can meet 32.8% of the thermal energy demand in the heating season and 84.6% of the energy consumption in non-heating season, with a yearly average solar fraction of 53.04%.

Alkilani et al. [57] achieved indoor prediction for output air temperature due to the discharge process in a solar air heater integrated with a PCM unit, for eight different values of mass flow as shown in Fig. 15. This system consists of a single-glazed solar air collector integrated with a PCM unit which is divided into cylinders as an absorber-container installed in the collector in a cross flow of pumped air. An indoor simulation supposed that the PCM initially at liquid phase (50 °C) heated by solar simulator while the pumped air over the cylinders at room temperature (28 °C), the mass flow rate, output air temperature, and the freezing time of PCM, represent important factors, eight steps of mass flow rate were started by 0.05–0.19 kg/s. The PCM consists of paraffin wax with mass fraction 0.5% aluminum powder to enhance the heat transfer, the freezing time for the PCM unit has been predicted for each mass flow rate, the freezing time of the PCM cylinders was related inversely to the mass flow rate, and took longer time approximately (8 h) with flow rate of 0.05 kg/s.

Jain and Jain [58] presented a transient analytical model for an inclined multi-pass solar air heater with in-built thermal storage and attached with the deep-bed dryer. This study was done for a day of the month of October for the climatic condition of Delhi (India). They studied the effect of change in the tilt angle, length and breadth of a collector and mass flow rate on the temperature. The grain temperature increases with the increase of collector length, breadth and tilt angle up to typical value of these parameters. The thermal energy storage also affects during the off-sunshine hours and is very pertinent for crop drying applications. The proposed mathematical model is useful for evaluating the thermal performance of a flat plate solar air heater for the grain drying applications. It is also useful to predict the moisture content, grain temperature, humidity of drying air and drying rate in the grain bed. Fath [59] designed and analyzed thermal performance of a simple design solar air heater with built-in thermal energy storage system. The heater absorber consists of a corrugated set of tubes filled with a phase change material (paraffin wax) as a thermal energy storage material. In this study, the absorber projected area was used 1.0 m^2, the length being 150 cm and the width 67 cm. The depth of the heater is taken to be equal to 7.5 cm. The system shows a 63.35% daily average efficiency an air flow rate of 0.02 kg/s, and the hot air outlet temperature (5 °C above ambient temperature) extended for about 16 h, as compared to 38.7% and 9 h, respectively, for the conventional flat plate air heater. For an air flow rate of 0.01 kg/s, the hot air outlet temperature continues for 21 h of the 24 h/day.

Tyagi et al. [20] experimentally studied the solar air heating system with and without thermal energy storage (TES) material for energy and exergy analyses (see Fig. 16). The paraffin wax as latent heat storage and hytherm oil for sensible heat storage were used in this study. They calculated the first law and the second law efficiencies on basis of the experimental observations with respect to the available solar radiation for three different arrangements, viz. one arrangement without heat storage material and two arrangements with THES, viz. hytherm oil and paraffin wax, respectively. They found fruitful observation in case of air heater with out and with heat storage material/fluid some are given below: they noted that the fluctuation in both the efficiencies which is mainly due to the fact that solar radiation also fluctuates throughout the day. In addition, as time increases, both the efficiencies first increase and then decrease in case without temporary storage material and the similar trend is found for solar radiation. In case of without THES material, the efficiency increases with time, attains its peak in the first half in general and then decreases after that. However, in cases where temporary heat storage material is used, both the efficiencies increase with time, attain their peaks at approximately 16:30 h with a small fluctuation with flow rate and then decrease smoothly. On the other hand, the results obtained in this study will be very useful and informative for real-life applications using PCMs storage in both the solar collector and in the thermal energy utilities for better performance.

Benli and Durmus [60] studied the thermal performance of solar air collectors heating system with phase change material for space heating of a greenhouse. $CaCl_2{\cdot}6H_2O$ was used as PCM in thermal energy storage with a melting temperature of 29 °C. In this system, the hot air delivered by 10 pieced solar air collector was passed through the PCM to charge the storage unit. The stored heat was utilized to heat ambient air before being admitted to a greenhouse (see Fig. 17). Through this study, they concluded that the solar air collectors and PCM system created 6–9 °C temperature difference between the inside and outside the greenhouse. The system worked more efficiently in day with high solar radiation

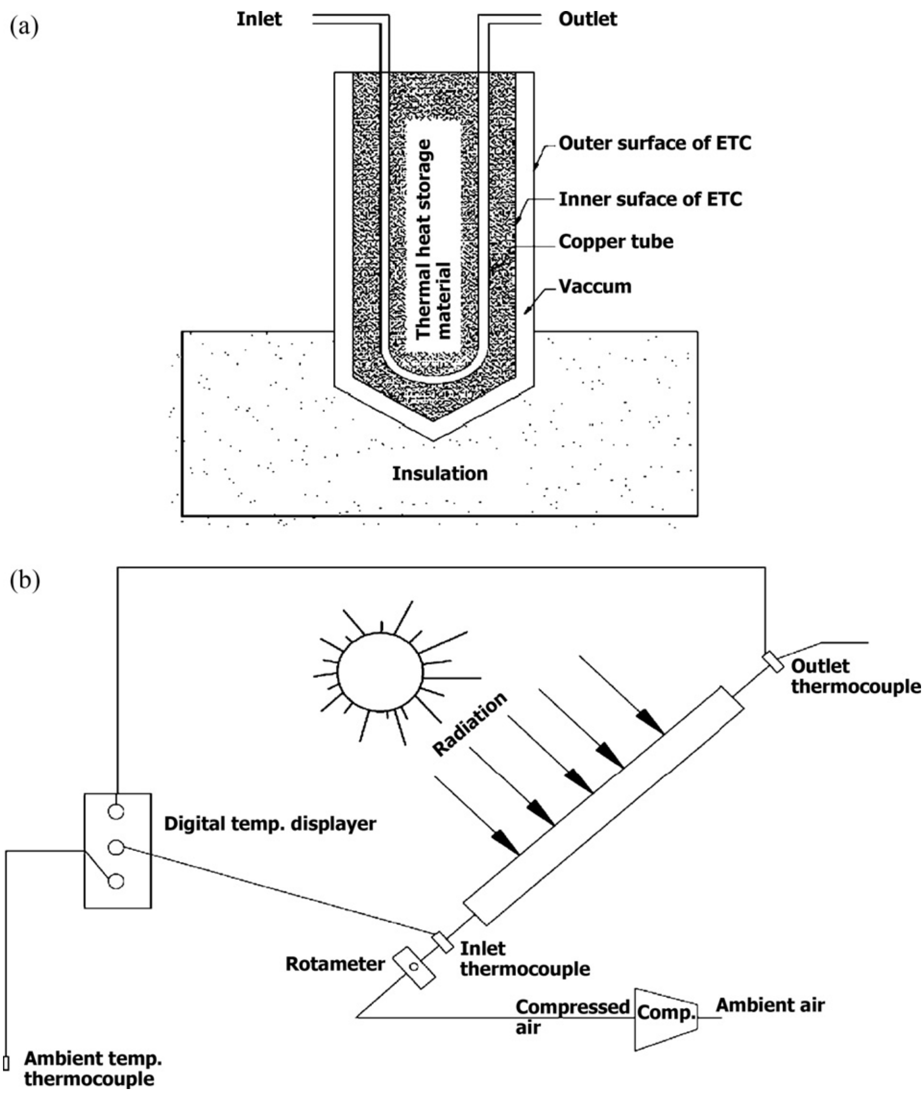


Fig. 16. (a) Cross-sectional view of ETC tube with THES and (b) schematic of the experimental set-up.

air temperatures. The proposed size of collectors integrated PCM provided about 18–23% of total daily thermal energy requirements of the greenhouse for 3–4 h, in comparison with the conventional heating device. Enibe [61] designed and carried out performance evaluation of a single-glazed flat plate collector passive solar air heating system integrated with a phase change material (PCM) heat storage assembly, which has potential applications in crop drying (see Fig. 18). The PCM is prepared in modules, with the

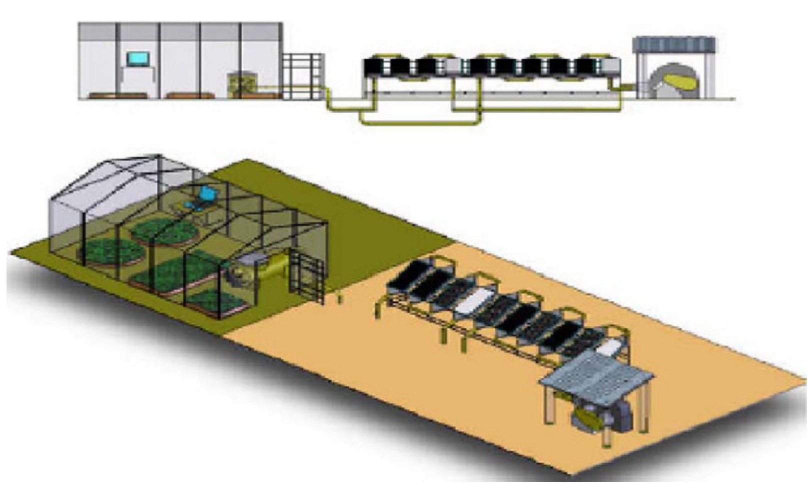


Fig. 17. Schematic views of green house heating system with thermal energy storage unit.



Fig. 18. Photograph of the air heating system (A: collector assembly with energy storage and air-heating subsystems; B: heated space).

modules equispaced across the absorber plate. The spaces between the module pairs serve as the air heating channels, the channels being connected to common air inlet and discharge headers. They tested experimentally air heating system under daytime no-load conditions at Nsukka, Nigeria, over the ambient temperature range of 19–41 °C, and a daily global irradiation range of 4.9–19.9 MJ m^2. Peak temperature rise of the heated air was about 15 K, while the maximum airflow rate and peak cumulative useful efficiency were about 0.058 kg/s and 22%, respectively. These results of the system show that the system can be operated successfully for crop drying applications.

Saman et al. [62] studied the thermal performance of a phase change thermal storage unit based solar roof integrated heating system. The storage unit was a component of a roof integrated solar heating system being developed for space heating of a home as shown in Fig. 19 [63]. The storage unit consists of several layers of phase change material (PCM) slabs with a melting temperature of 29 °C. The warm air was circulated in a roof integrated collector and passed through the spaces between the PCM layers to charge the storage unit. The stored energy in form of heat was utilized to heat ambient air before being admitted to a living space. They concluded some useful remarks for this study.

For heating purpose, system showed a significant warming effect during the initial periods of delivering air to the living space. This is advantageous from the thermal comfort point of view.

(1) The effect of sensible heat is perceived in the initial periods of both melting and freezing. The effect is reflected in sharp increase in the outlet air temperature in the initial periods of melting and a sharp decrease in the initial periods of freezing.
(2) A higher inlet air temperature increases the heat transfer rates and shortens the melting time. Conversely, during freezing, a lower inlet air temperature increases the heat transfer rates and shortens the freezing time.

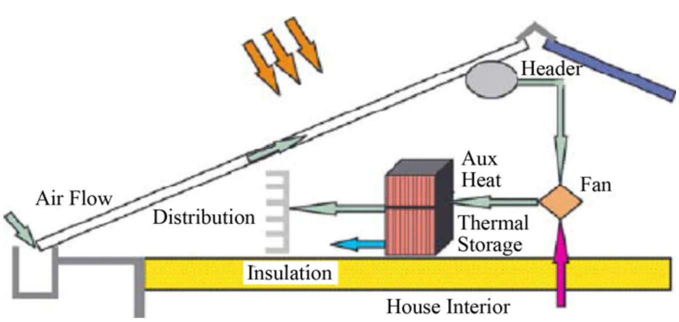


Fig. 19. Solar roof integrated heating system with storage unit.

5. Hybrid photovoltaic/thermal (PV/T) solar air heater

Photovoltaic (PV) solar panels generally produce electricity in the 5–20% efficiency range, depending on the type of solar cell and the rest being dissipated in thermal losses [64]. To recover the thermal losses hybrid photovoltaic thermal systems (PV/T) are recommended. Hybrid photovoltaic/thermal (or simply PV/T) solar collector produces both thermal energy and electricity simultaneously [65,66]. A PV/T collector typically consists of a PV module; on the back of which an absorber plate (a heat extraction device) is attached as shown in Fig. 20. The purpose of the absorber plate is twofold. Firstly, to cool the PV module and thus improve its electrical performance (electrical efficiency losses amount to 0.4% for each degree of increase of cell temperature with reference to standard test conditions (STC): 25 °C, $q'' = 1000\,\mathrm{W/m^2}$) and secondly to collect the thermal energy produced, which would have otherwise been lost as heat to the environment [67]. The most available literature on hybrid photovoltaic thermal systems (PV/T) is presented here.

Sarhaddi et al. [68] developed the thermal and electrical model to calculate the thermal and electrical parameters of a typical PV/T air collector. It was predicted that, the electrical efficiency of a PV/T air collector has a slight change with respect to operating and design parameters. The overall energy efficiency of a PV/T air collector is always greater than the thermal efficiency of a solar collector or the electrical efficiency of a PV module. When inlet air temperature or wind speed or duct length increases, the overall energy efficiency and thermal efficiency of system decrease. While inlet air velocity is increasing, the overall energy efficiency and thermal efficiency of a PV/T air collector increase. It was also found that while increasing the solar radiation intensity, the overall energy efficiency and electrical efficiency of a PV/T air collector increase initially and then decrease after attaining solar radiation intensity of about a maximum point.

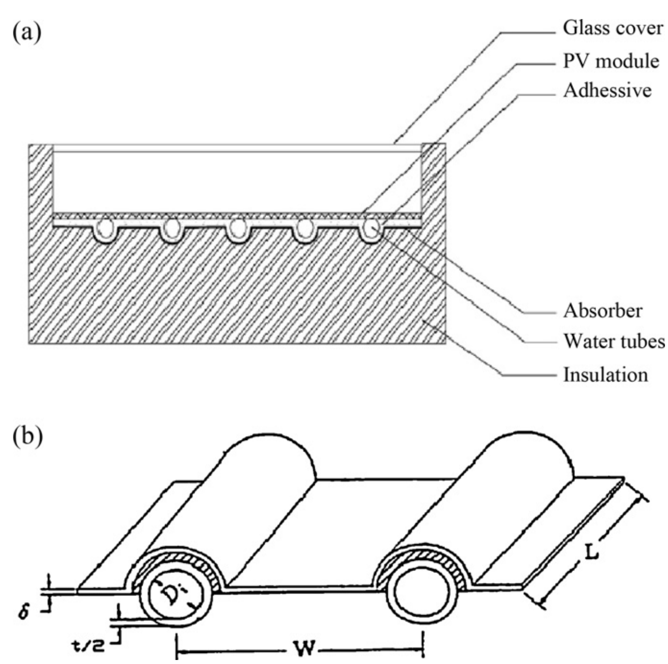


Fig. 20. PV/T collector (a) cross section of a PV/T collector and (b) schematic of an absorber plate showing the various dimensions [64].

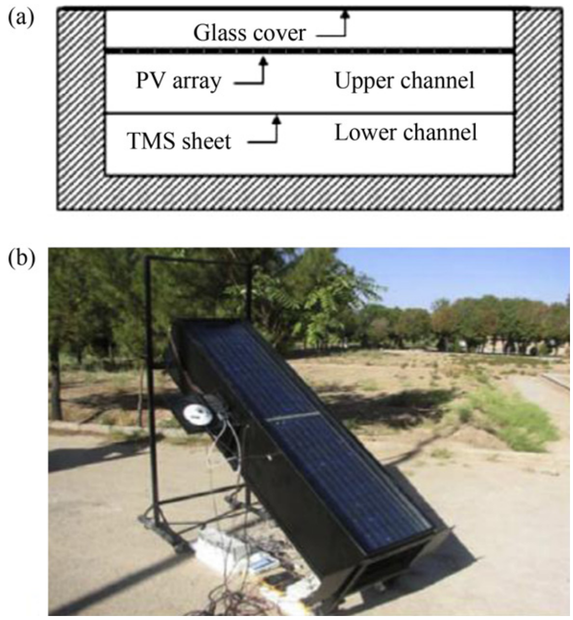


Fig. 21. (a) Cross-sectional view of studied PV/T air collector. (b) Photograph of experimental setup.

Photovoltaic/thermal (PV/T) systems refer to the incorporation of photovoltaic and solar thermal technologies into one single structure, by which both useful heat and electricity energy can be produced. Direct-coupled PV/T air collector was designed, built, and tested at a geographic location of Kerman, Iran by Shahsavar and Ameri [69]. In this system panels were connected in parallel and mounted on the air channel and above a thin metal (aluminum) sheet (TMS). This aluminum sheet was suspended at the middle of air channel as a secondary absorber plate and used to improve heat extraction from the panels (by increasing heat exchange surface) and consequently achieving higher thermal and electrical outputs. The air channel casing built from Medium Density Fiberboard (MDF) wood as illustrated in Fig. 21. This PV/T system was tested in natural convection and forced convection (with two, four and eight fans operating). During the experiments it found that in the case of forced convection, air mass flow rate decreases by setting glass cover on photovoltaic panels. On the other hand, in free convection mode, setting glass cover leads to air mass flow rate increases. Thermal efficiency increases with increasing the air mass flow rate due to increased heat transfer coefficient. Setting glass cover on photovoltaic panels leads to an increase in thermal efficiency and a decrease in electrical efficiency of the system.

Energy and exergy efficiencies of a hybrid photovoltaic–thermal (PV/T) air collector Srinagar (India) condition were estimated by Joshi and Tiwari [70]. It was found that there is an increase of about 2–3% exergy due to thermal energy in addition to its 12% electrical output from PV/T system, which makes an overall electrical efficiency of about 14–15% of PV/T system. A numerical study of various PV/T of concepts was conducted by Zondag et al. [71] and it was found that the uncovered sheet and tube collectors present a poor thermal performance due to the large top heat losses to the environment. On the other hand, they explained that the electrical efficiency of sheet and tube collectors is dramatically reduced due to the reduced transmittance of radiation reaching the PV cells.

Cox and Raghuraman [72] performed computer simulations to optimize the design of flat-plate photovoltaic/thermal solar collectors so as to yield the highest values of both electrical and thermal efficiencies. They concluded that increasing the solar

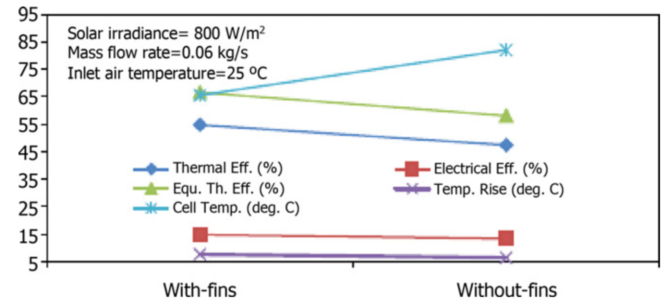


Fig. 22. Comparison of values of various efficiencies and the rise in air and cell temperatures for a solar PV/T system with and without fins.

absorptance of the collectors and decreasing the collector losses through use of a heat-mirror coating, like ITO (indium tin oxide), above the cells. On the strength of the simulation results, the following conclusions can be drawn: (1) For photovoltaic cells covering more than 65% of the total collector area, a selective absorber actually reduces the collector thermal efficiency when used with a gridded-back cell (one that transmits insolation above a wavelength of 1.1 μm). (2) The requirements of a heat-mirror coating, like ITO, based on trade-offs between decreasing emissivity and decreased solar transmittance, are an infrared emissivity of less than 0.25 and solar transmissivity of greater than 0.85. (3) The optimum combination of an air PV/T collector was found to consist of gridded-back PV cells, a nonselective secondary absorber, and a high transmissivity/low emissivity heat-mirror cover above the photovoltaic cells. Performance of photovoltaic/thermal (PV/T) solar air heater with a double pass configuration and vertical fins in the lower channel under steady state conditions was investigated by Kumar and Rosen [73]. They reported that the thermal and electrical efficiencies are significantly improved by the addition of fins on the back side of the absorber surface as illustrated in Fig. 22. Huang et al. [74] evaluate the performance of the integration of solar photovoltaic and thermal systems (IPVTS). The experimental results comprehensively compared with the conventional solar water heater. Schematic of IPVTS is shown in Fig. 23, the polycrystalline PV module has been integrated with the thermal collector made from a corrugated polycarbonate panel with sheet and tube heat collecting plate made of copper. They concluded that the solar PV/T collector made from corrugated polycarbonate panel produced good thermal efficiency. They suggested that further improvement can be achieved by proper insulation for the PV/T design.

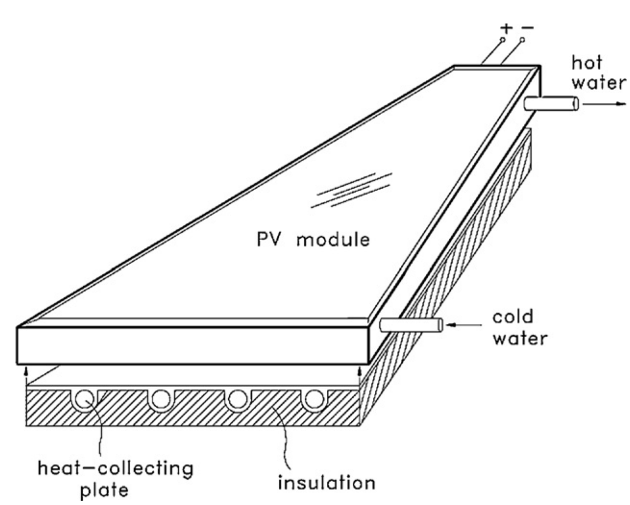


Fig. 23. Schematic diagram of PV/T collector.

6. Conclusions

Solar air heater is a simple device which captures the solar energy. Producing hot air by using solar air heater is a renewable energy heating technology used to process heat generation or space heating. Such systems produce heat at zero cost, using sun as energy source and it is freely available. It requires minimum maintenance like cleaning of collectors only is required. Energy storage not only plays an important role in conservation of the energy but also improves the performance and reliability in wide range of energy systems and becomes more important where the energy source is intermittent in nature such as solar. Energy storage process reduces the rate of mismatch between energy supply and its demand. The thermal energy storage can be used in such places where more variation in temperature difference between day and night. In this comprehensive review, a detailed research work is accumulated for air heating system without thermal energy storage, latent heat storage based air heating system and PV/T hybrid air heating systems. It can also be concluded that from these comprehensive reviews lot of works have been carried out globally to evaluate the performance of different types of solar air heaters. Mostly flat plate air heater produces hot air at low temperature and found suitable for drying agricultural products. Hybrid PV/T type solar air heater shows their viability in force convection type air heating with electricity production. Various investigators have developed thermal energy storage type air heater for effective and efficient utilization of hot air for space heating. Many investigations reported that PCM based thermal energy storage solar heater is suitable for crop drying applications.

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